The path to 5G: Cellular Vehicle-to-Everything (C-V2X)
Our vision for the autonomous vehicle of the future

A safer, more efficient, and more enjoyable experience

- Safer: Towards zero road accidents
- Greener: Reduce air pollution and emissions
- Efficient: More predictable and productive travel

Intelligently connected
Efficiently shared
Increasingly electric
Increasingly autonomous
5G will be a key enabler for our automotive vision

Providing a unifying connectivity fabric for the autonomous vehicle of the future

Enhanced mobile broadband

Mission-critical services

Massive Internet of Things

Unifying connectivity platform for future innovation

Convergence of spectrum types/bands, diverse services, and deployments, with new technologies to enable a robust, future-proof 5G platform; Starting today with Gigabit LTE, C-V2X Rel-14, and massive IoT deeper coverage
Paving the road to tomorrow’s autonomous vehicles

Leveraging essential innovations in wireless and compute

Unified connectivity

- Providing always-available, 4G/5G secure cloud access for vehicles
- Vehicle-to-Everything (V2X) communications

3D mapping and precise positioning

- Active ranging and positioning
- Embedded GNSS with DR
- VIO/lane-level accuracy
- Cloud Based Assistance for 3D mapping

On-board intelligence

- Heterogeneous computing
- On-board machine learning
- Computer vision
- Sensor fusion
- Intuitive security

Autonomous car

Power optimized processing for the vehicle
Fusion of information from multiple sensors/sources

1. Dead Reckoning, 2 Visual-Inertial Odometry
V2X is a critical component for safer autonomous driving

Communicating intent and sensor data even in challenging real world conditions

**Non line-of-sight sensing**
Provides 360° NLOS awareness

- E.g. intersections/on-ramps, environmental conditions (rain/fog/snow)
- Blind intersection/vulnerable road user (VRU) alerts

**Conveying intent**
Communicates intent and share sensor data to provide higher level of predictability

- Road hazard
- Sudden lane change

**Situational awareness**
Offers increased electronic horizon to enable soft safety alerts and reliable graduated warning

- Reduced speed ahead
- Queue warning/shockwave damping

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**Vehicle-to-vehicle (V2V)**
e.g. collision avoidance safety systems

**Vehicle-to-pedestrian (V2P)**
e.g. safety alerts to pedestrians, bicyclists

**Vehicle-to-infrastructure (V2I)**
e.g. traffic light optimal speed advisory

**Vehicle-to-network (V2N)**
e.g. real-time traffic / routing, cloud services
V2X provides higher level of predictability and autonomy

Complementing other sensor technologies

**Radar**
- Bad weather conditions
- Long range
- Low light situations

**Camera**
- Interprets objects/signs
- Practical cost and FOV

**Lidar**
- Depth perception
- Medium range

**Ultrasonic**
- Low cost
- Short range

**V2X wireless sensor**
- See through, 360° non-line of sight sensing, extended range sensing

**3D HD maps**
- HD live map update
- Sub-meter level accuracy of landmarks

**Precise positioning**
- GNSS positioning
- Dead reckoning
- VIO

**Brain of the car to help automate the driving process by using:**
- Immense compute resources
- Sensor fusion
- Machine learning
- Path planning
Continuous V2X technology evolution required

Basic safety
802.11p or C-V2X R14

Enhanced safety
C-V2X R14

- Enhanced communication’s range and reliability
  - Supports higher speeds and additional safety needs, e.g., in NLOS and challenging road conditions

Advanced safety
C-V2X R15+ (building upon R14)

- Higher throughput
  - Up to 1Gbps for sensor sharing
- Higher reliability
  - Up to 99.999% for automated driving
- Wideband carrier support
  - For accurate ranging and positioning
- Lower latency
  - ~1ms for automated driving

Established foundation for V2X

Continuous technology evolution to 5G while maintaining backward compatibility
Supporting rapidly evolving safety requirements and use cases

Continuous technology evolution to 5G while maintaining backward compatibility

**Basic safety**
802.11p or C-V2X R14

**E.g. day 1 use cases**
- Forward collision warning and basic platooning
- Blind curve hazard warning
- Icy road

**Enhanced safety**
C-V2X R14

- Extending electronic horizon, providing more reliability and NLOS performance

**Advanced safety**
C-V2X R15+ (building upon R14)

- For autonomous driving in real world conditions
- High throughput communications for sensor sharing
- Partially to highly automated driving
- Cooperative driving

**Examples**
- Forward collision warning
- Blind curve hazard warning
- Icy road

**Key Points**
- Continuous evolution to 5G while maintaining backward compatibility
- Basic safety (802.11p or C-V2X R14)
- Enhanced safety (C-V2X R14)
- Advanced safety (C-V2X R15+)
- Various use cases for autonomous driving
C-V2X enhances range and reliability for safer driving

Paving the path to the autonomous vehicle of the future
The path to 5G will enable safer, autonomous driving
Starting with C-V2X release 14 - specification completion and global trials in 2017

Synergistic with existing automotive cellular connectivity platform
Cellular already delivering key services today, e.g. telematics, eCall, connected infotainment

Delivers enhanced range and reliability for V2X direct communications
Improvements over 802.11p, ~2x range, or more reliable performance at the same range

Leverages existing cellular infrastructure for network communications
Offering new business models and economic benefits (e.g. combined RSUs and eNBs)

Rich roadmap towards 5G with strong ecosystem (infra, MNO, smartphone)
Technology evolution to address expanding capabilities/use cases

1. 60% Cellular penetration in new light vehicles sales by 2021; 2. Based on Qualcomm Research simulations
C-V2X defines two complementary transmission modes

**Direct communications**
V2V, V2I, and V2P on “PC5” Interface, operating in ITS bands (e.g. ITS 5.9 GHz) independent of cellular network.

**PC5 interface**
e.g. location, speed

V2I (PC5)  
V2V (PC5)  
V2P (PC5)

**Network communications**
V2N on “Uu” interface operates in traditional mobile broadband licensed spectrum.

**Uu interface**
e.g. accident 2 kilometer ahead

V2N (Uu)  
eNodeB

V2N (Uu)

PCS operates on 5.9GHz; whereas, Uu operates on commercial cellular licensed spectrum.
C-V2X is designed to work without network assistance. V2V/V2I/V2P direct communications enables low latency applications.

**USIM-less operation**
- C-V2X direct communications doesn’t require USIM

**Autonomous resource selection**
- Distributed scheduling, where the car selects resources from resource pools without network assistance

**GNSS time synchronization**
- Besides positioning, C-V2X also uses GNSS for time synchronization without relying on cellular networks

1. 3GPP also defines a mode, where eNodeB helps coordinate C-V2X Direct Communication; 2. GNSS is required for V2X technologies, including 802.11p, for positioning. Timing is calculated as part of the position calculations and it requires smaller number of satellites than those needed for positioning.

Direct communications (via PC5 interface on 5.9GHz)
C-V2X is designed to work in ITS 5.9 GHz spectrum

For vehicles to talk to each other on harmonized, dedicated spectrum

**3GPP support of ITS 5.9 GHz band**
C-V2X support in ITS band was added in 3GPP Release 14\(^1\)

**Harmonized spectrum for safety**
C-V2X uses harmonized/common, dedicated spectrum for vehicles to talk to each other

**Coexistence with 802.11p**
C-V2X and 802.11p can co-exist by being placed on different channels in the ITS band

1 GHz support began in release 13 with LAA, and expanded with release 14 for ITS
C-V2X reuses upper layers defined by automotive industry

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Applications</td>
<td>Safety and non-safety</td>
</tr>
<tr>
<td>Message / Facilities layer</td>
<td>Reuse established service and app layers</td>
</tr>
<tr>
<td>- IEEE / ETSI / ISO</td>
<td>• Already defined by automotive and standards communities, e.g. ETSI, SAE</td>
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<tr>
<td>- UDP / TCP</td>
<td>• Developing abstraction layer to interface with 3GPP lower layers (in conjunction with 5GAA)</td>
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<tr>
<td>- IPv6</td>
<td>• Supports the ever-evolving V2X use cases</td>
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<tr>
<td>Non-IP</td>
<td>Reuse existing security and transport layers</td>
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<tr>
<td>- ProSe Signaling</td>
<td>• Defined by ISO, ETSI, and IEEE 1609 family</td>
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<td>- PDCP</td>
<td>Continuous enhancements to the radio/lower layers</td>
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<td>- RLC</td>
<td>• Supports the ever-evolving V2X use cases</td>
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<tr>
<td>- MAC</td>
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<td>- PHY</td>
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Note: Also enhancements to the LTE Direct network architecture / system design to support V2X
C-V2X Rel-14 has significantly better link budget than 802.11p\(^1\)

Leading to longer range (~2X range)—or more reliable performance at the same range

**Transmission time**
Longer transmit time leads to better energy per bit

Energy per bit is accumulated over a longer period of time for C-V2X

**Waveform**
SC-FDM has better transmission efficiency

SC-DFM allows for more transmit power than OFDM for the same power amplifier

**Channel coding**
Gains from turbo coding and retransmission

Coding gain from turbo codes and HARQ retransmission lead to longer range

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\(^1\) Link budget of C-V2X is around 8 dB better than 802.11p
Providing better support for enhanced safety use cases

By extending electronic horizon, providing more reliability, and better NLOS performance

- Do not pass warning (DNPW)
- Blind curve/local hazard warning
- Road works warning
- Intersection movement assist (IMA) at a blind intersection
- Vulnerable road user (VRU) alerts at a blind intersection
- Left turn assist (LTA)
More reliability at higher speeds and varying road conditions

Disabled vehicle after blind curve use case example

Icy road condition

- C-V2X: 38mph
- 802.11p: 28mph

Normal road condition

- C-V2X: 63mph
- 802.11p: 46mph

Stopping distance estimation\(^1\)

(Driver reaction time + braking distance)

\[ \text{Stopping Distance} = (\text{Driver reaction time} + \text{braking distance}) \]

\[ \text{C-V2X (107m) DSRC (60m)} \]

\(^1\) Consistent with CAMP Deceleration Model and AASHTO *green book,*
More reliability at higher speeds and longer ranges

Do not pass warning (DNPW) use case example

**C-V2X**

- 43 mph
- 443 m

**802.11p**

- 28 mph
- 240 m

### Required passing alert distance (m) vs. speed (mph)

- **C-V2X**
  - DNPW range: 443 m
- **DSRC**
  - DNPW range: 240 m

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1. Calculations based on AASHTO “green book”
Gaining momentum and broad ecosystem support
C-V2X is gaining momentum

Trials starting in 2017 with commercial solutions planned soon thereafter

Trials starting in 2017

ConVeX trial in Germany
Qualcomm, Audi, Ericsson, SWARCO, U. of Kaiserslautern

Other trials
Planned globally throughout 2018

The first announced C-V2X trial based upon 3GPP Release 14

UK, France, US, Japan, Korea and China

Initial C-V2X spec. completed in 2016
C-V2X gaining support from automotive and telecom leaders

5GAA is a cross-industry consortia helps define 5G V2X communications

Automotive industry
Vehicle platform, hardware, and software solutions

Telecommunications
Connectivity and networking systems, devices, and technologies

End-to-end solutions for intelligent transportation mobility systems and smart cities

Audi  BMW  MINI  Rolls-Royce  China Mobile  Continental  Daimler  Danlaw
Denso  Ericsson  Ficosa  Ford  Gemalto  Huawei  Intel  LG
NTT DoCoMo  Qualcomm  Rohde & Schwarz  Saic Motor  Samsung  SK Telecom
T Mobile  Valeo  Verizon  VLAVI  Vodafone  ZTE  Nokia

Source: [http://5gaa.org/](http://5gaa.org/); accurate as of February 1st, 2017
Advanced services further enabled by V2V+V2I+V2P+V2N

Offering new business models and enhancing most use cases

Most use cases use a combination of interfaces

V2N provides over-the-top cloud services

V2P enhances safety for vulnerable road-users

RSUs combined with eNodeBs or standalone roadside devices

RSUs can connect to network for cloud services

V2I allows RSU's to monitor traffic, e.g. traffic signals, tolls

V2V mostly for safety and ADAS services
C-V2X offers new business models and economic benefits

Leveraging existing, ubiquitous cellular networks and mobile ecosystem support

- **Reduced deployment cost**: Combined RSU and eNodeB infrastructure synergies provide economic benefits.
- **More integrated solution**: C-V2X functionality can be integrated in vehicle’s modem to enable most optimal platform.
- **Mobile ecosystem expertise**: Benefits from cellular player’s extensive experience in deploying, managing, and maintaining complex communication systems.
- **New services and business opportunities**: Leverages unified C-V2X / telematics offerings and addresses new services for shared mobility and autonomous driving.
5G will bring new capabilities for autonomous vehicles

While maintaining backward compatibility
5G will redefine a wide range of industries
A platform for new connected services—existing, emerging and unforeseen

Immersive entertainment and experiences
Safer, more autonomous transportation
Reliable access to remote healthcare
Improved public safety and security
More efficient use of energy/utilities
More autonomous manufacturing
Sustainable cities and infrastructure
Digitized logistics and retail

>$12 Trillion
Worth of goods and services by 2035

Learn more at: 5G Economy Study
LTE Advanced Pro establishes the foundation for 5G
Pioneering 5G NR technologies and verticals

Significantly improve performance, scalability, and efficiency

5G New Radio (NR)
- Multi-Gbps eMBB (sub-6 GHz and mmWave)
- NR-based LAA
- Ultra-reliable & low-latency
- NR-Based mMTC
- Further enhancements and new capabilities

5G
- NR-Based mMTC
- Further enhancements towards IMT-2020 in existing spectrum

LTE Advanced Pro
- Rel-13: Today
- Rel-14
- Rel-15
- Rel-16+

New verticals
- Cellular V2X (C-V2X)
- Ultra-low latency
- Digital TV
- Internet of Things
- Unlicensed spectrum
- Mobile broadband

- eMBMS enhancements
- eMTC, NB-IoT
- LAA
- Gigabit LTE
- C-V2X safety features
- New C-V2X capabilities
- Ultra-low latency
- enTV, e.g., shared broadcast
- FeMTC, eNB-IoT
- eLAA
- Enhancements, e.g., FD-MIMO

Further enhancements towards IMT-2020 in existing spectrum
Path to 5G enables a broad set of automotive use cases

C-V2X establishes the foundation for safety services

**Internet of Things**

- **LTE IoT today**
  - Enables remote sensing and control in deep coverage conditions

**Mobile broadband**

- **5G NR eMBB Release 15+**
  - Multi gigabit downlink for streaming, VR/AR and 3D high def. maps; and uplink for remote supervisory control

**C-V2X**

- **C-V2X Release 14**
  - Provides highly reliable, real-time communication for automotive safety use cases

- **C-V2X Release 15+**
  - Augments Rel-14 with complementary and new capabilities (e.g. sensor sharing); while maintaining backward compatibility

**Massive IoT Release 16+**

- New capabilities and further optimizations (e.g., multi-hop mesh for deeper coverage, lower power)
5G V2X brings new capabilities for the connected vehicle

While maintaining backward compatibility

Wideband ranging and positioning
Wideband carrier support to obtain accurate positioning and ranging for cooperated and automated use cases

High throughput sensor sharing
High throughput and low-latency to enable the exchange of raw or processed data gathered through local sensors or live video images

Local high definition maps / “Bird’s eye view”
High throughput to build local, dynamic maps based on camera and sensor data; and distribute them at street intersections

Wideband carrier support | High throughput | Ultra-low latency | Ultra-high reliability | Strong security
5G V2X brings new capabilities with backward compatibility.

- See-through / High throughput sensor sharing
- Wideband ranging and positioning
- Sensor fusion
- Send HD map updates to vehicles on the road
- Precise positioning / 3D mapping
- Bird’s eye view of intersection

Wideband carrier support | High throughput | Ultra-low latency | Ultra-high reliability | Strong security
Enabling safer, more automated driving

- Accurate positioning and ranging
- See-through / High throughput sensor sharing
- Send HD map updates to vehicles on the road
- Bird's eye view of intersection
Enabling the next gen of connected vehicle experiences

Sample use cases

Increased driver’s awareness
- e.g. Bird’s eye view of an intersection or see-through capability when driving behind a truck

Cooperative driving and collision avoidance
- e.g. Cooperative collision avoidance and high-density platooning which requires new levels of latency and reliability,

Fully autonomous driving
- e.g. Using real-time HD map update and precise positioning for automated driving
Fully leveraging ITS 5.9 GHz band for 5G V2X services

Supporting today’s basic safety, and tomorrow’s advanced use cases

Example 5.9 GHz

10 MHz
Support today’s safety use cases on small subset of the band (using 802.11p or C-V2X)

70 MHz
In addition to basic safety, support advanced safety services (e.g. higher bandwidth sensor sharing and wideband ranging/positioning)

C-V2X Rel-15+ can operate in the same Rel-14 spectrum
Continuous V2X technology evolution required
And careful spectrum planning to support this evolution

Evolution to 5G, while maintaining backward compatibility

Enhanced safety
C-V2X R14

Basic safety
802.11p or C-V2X R14

Established foundation for V2X

Longer range or more reliability

Advanced safety
C-V2X R15+ (building upon R14)

Higher throughput
Higher reliability
Wideband ranging and positioning
Lower latency
Qualcomm is accelerating the future of autonomous vehicles

- **V2X Wireless Sensor**
  - 802.11p (DSRC/ITS-G5)
  - C-V2X

- **3D HD Maps**
  - Semantic lane information
  - Landmark and lane coordinates for positioning

- **Precise positioning**
  - GNSS positioning
  - Dead reckoning
  - VIO

- **Heterogeneous connectivity**
  - Cellular 3G / 4G / 5G
  - Wi-Fi / BT
  - CAN / Ethernet / Powerline

- **On-board intelligence**
  - Heterogeneous computing
  - On-board machine learning
  - Computer vision
  - Sensor fusion
  - Intuitive security

**Power optimized processing for the vehicle**
- Fusion of information from multiple sensors/sources
- Path prediction, route planning, control feedback
Anyone can talk about 5G. We are creating it.
In summary

The evolutionary roadmap for C-V2X towards 5G will be key for safety and autonomous driving.

C-V2X provides a higher performance radio, reusing upper layers defined by the automotive industry.

Gaining momentum and broad ecosystem support.

Qualcomm is leading the way to 5G; accelerating the future of autonomous vehicles.

Learn more at: www.qualcomm.com/C-V2X
Questions? - Connect with Us

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Thank you